Astrophysics and Heliophysics from the Moon

… and Lunar Science, Astrobiology, and Exploration

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&

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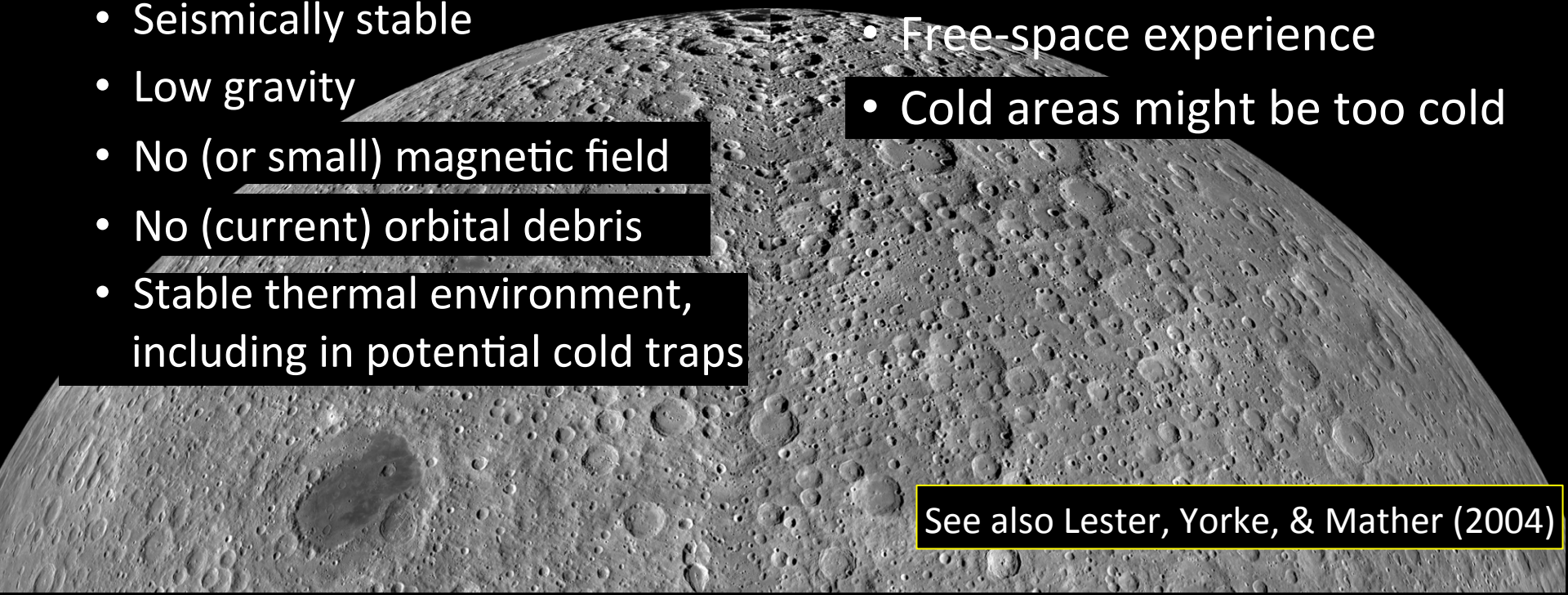
Science From The Moon
Why?

Advantages

- ➢ No (or almost no) atmosphere
- ➢ Tidally locked
- Seismically stable
- Low gravity
- No (or small) magnetic field
- No (current) orbital debris
- Stable thermal environment, including in potential cold traps

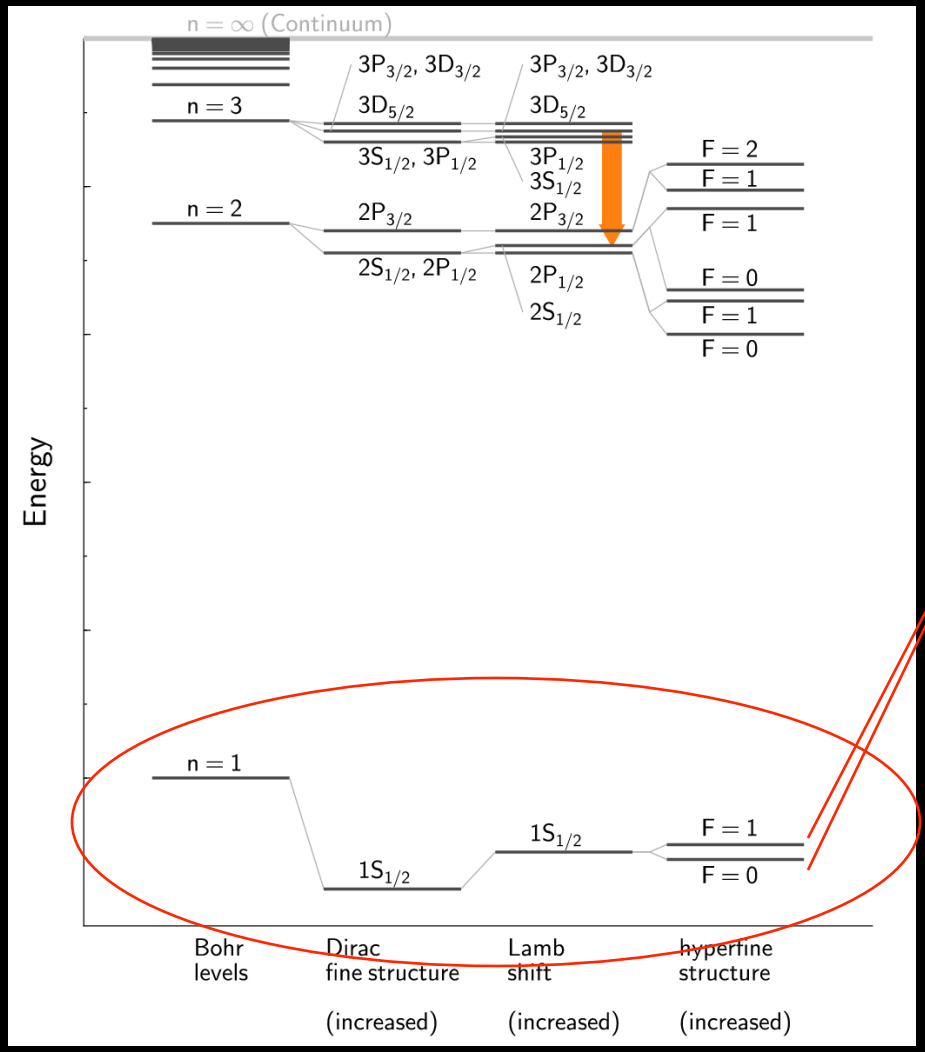
Disadvantages

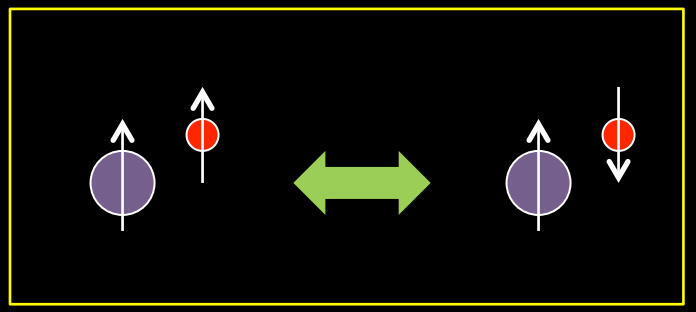
- Dust
- Non-zero gravity
- Free-space experience
- Cold areas might be too cold



See also Lester, Yorke, & Mather (2004)

Hydrogen Atom





$n = 1, F = 1 \rightarrow 0$

$E_{10} = h\nu = 5.8743253\ \mu eV$

$T_* = E_{10}/k = 0.068\ K$

$\nu = 1420.405752\ MHz$

$\lambda = 21\ cm$

Cosmic Dawn & Dark Ages

Hydrogen Signal

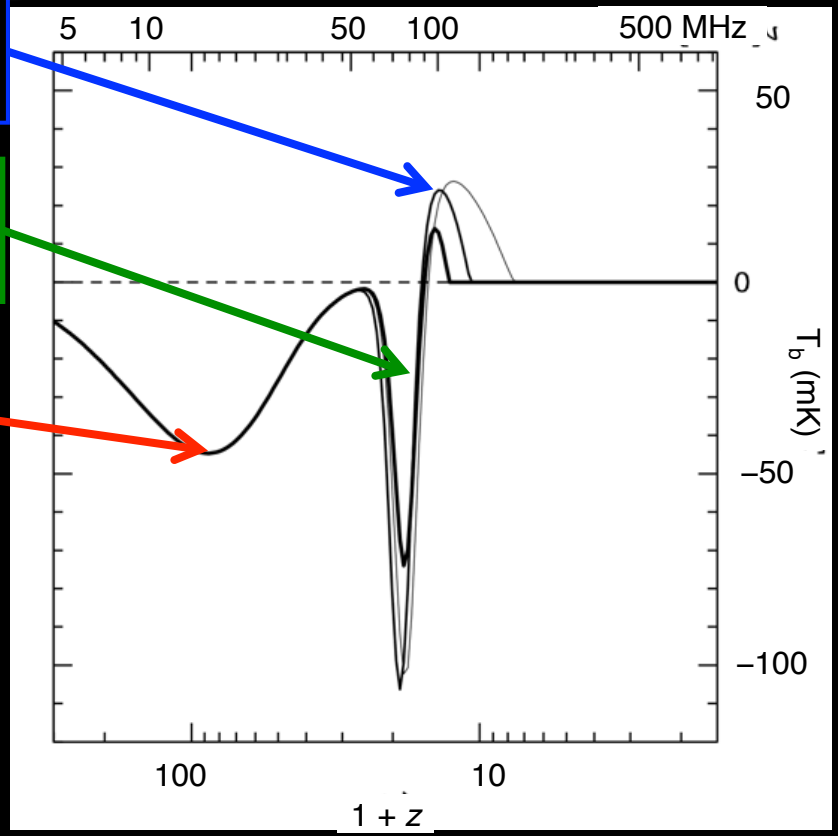
Neutral Hydrogen

Spin-flip transition provides probe of neutral intergalactic medium before and during formation of first stars

EoR

Cosmic Dawn

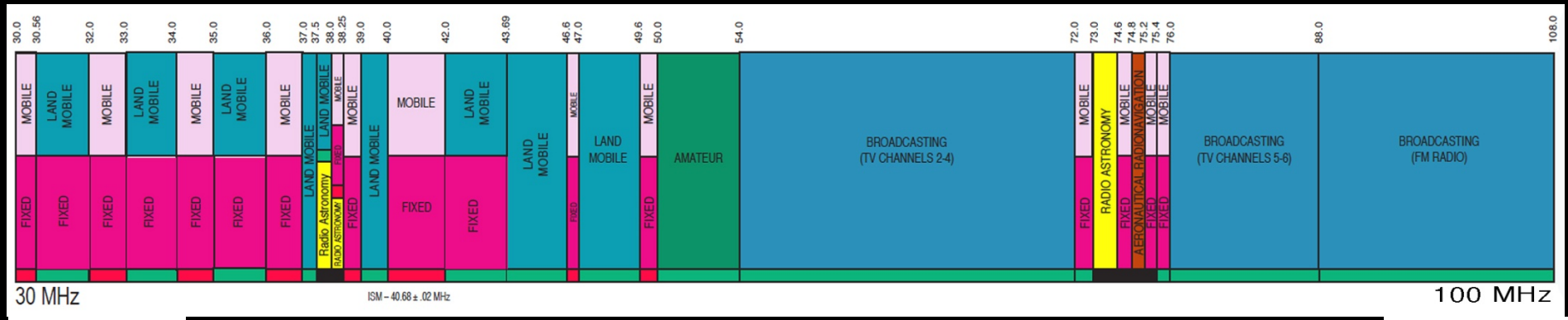
Dark Ages



$\nu = 1420\ \text{MHz}/(1 + z)$

$\lambda = 21\ \text{cm}\ (1 + z)$

Radio Spectrum



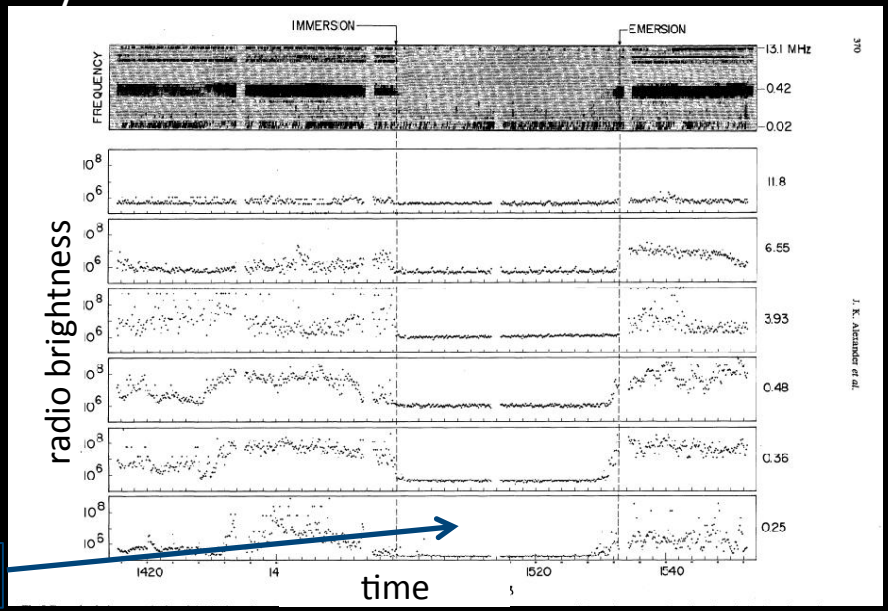
50 Myr since Big Bang

Portion of radio spectrum relevant for 21 cm observations of Cosmic Dawn and Dark Ages

- Yellow = reserved for radio astronomy

330 Myr since Big Bang

- Data from Radio Astronomy Explorer-2, when it passed behind the Moon, illustrating cessation of terrestrial emissions
- *Apollo* command modules lost communications when behind the Moon.



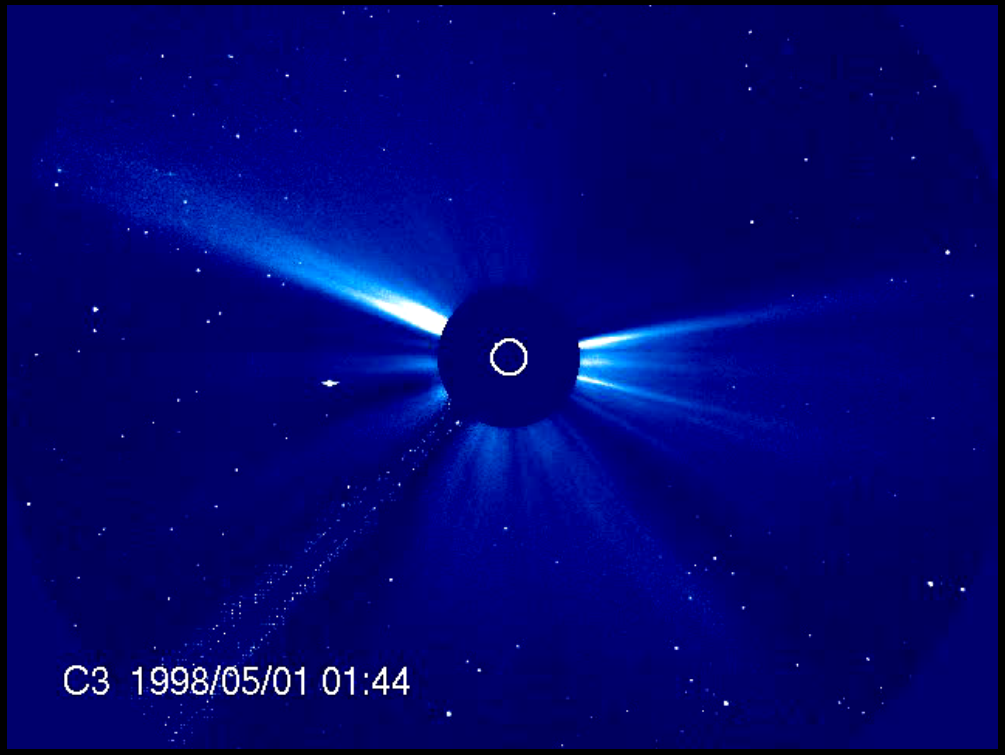
RAE-2 behind Moon

Radio Heliophysics
Space Weather

Coronal mass ejections (CMEs) emit large quantities of magnetized plasma into inner solar system

- Accelerate particles
  - How?
  - Where?
  - Relevance to larger (astro-)physical questions
- Can affect space systems and infrastructure

  E.g., Quebec power grid failure of 1989
- Can affect astronaut health

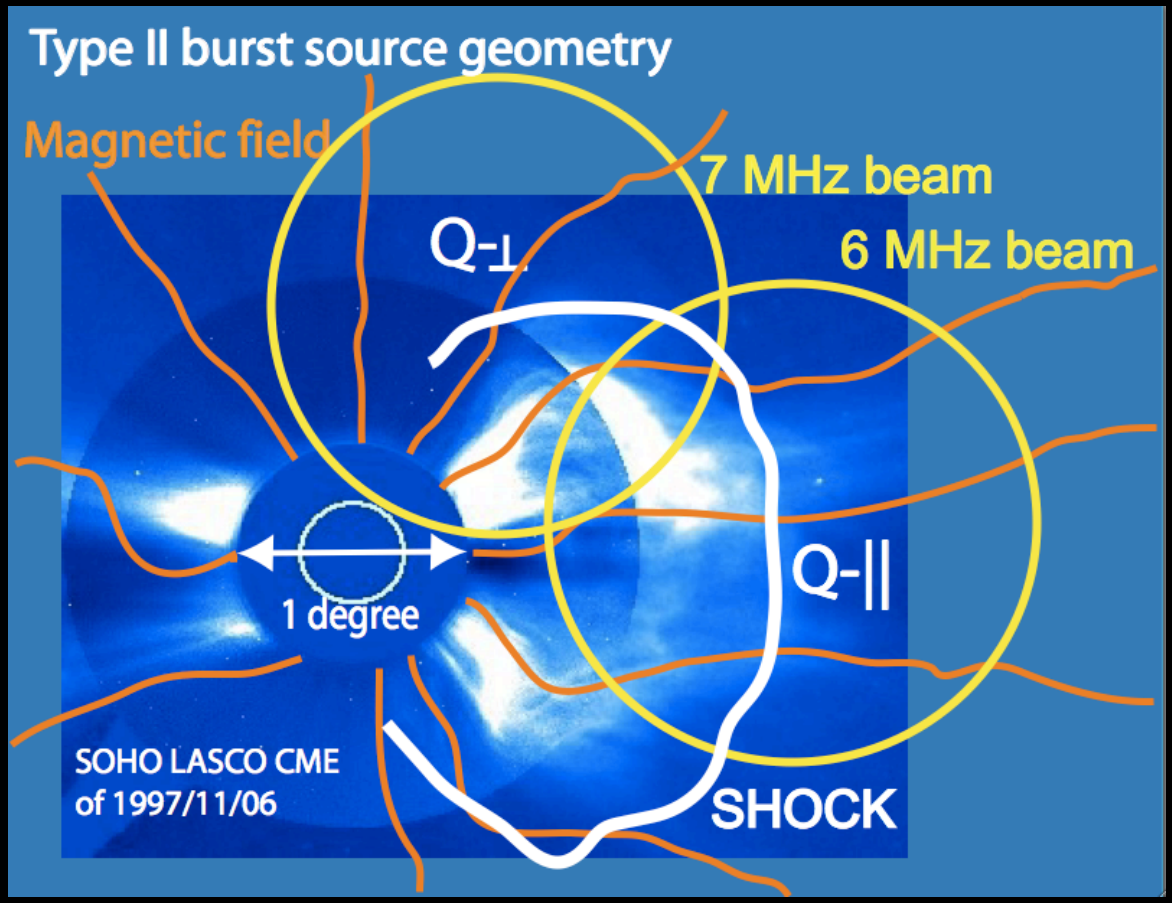


Radio Heliophysics

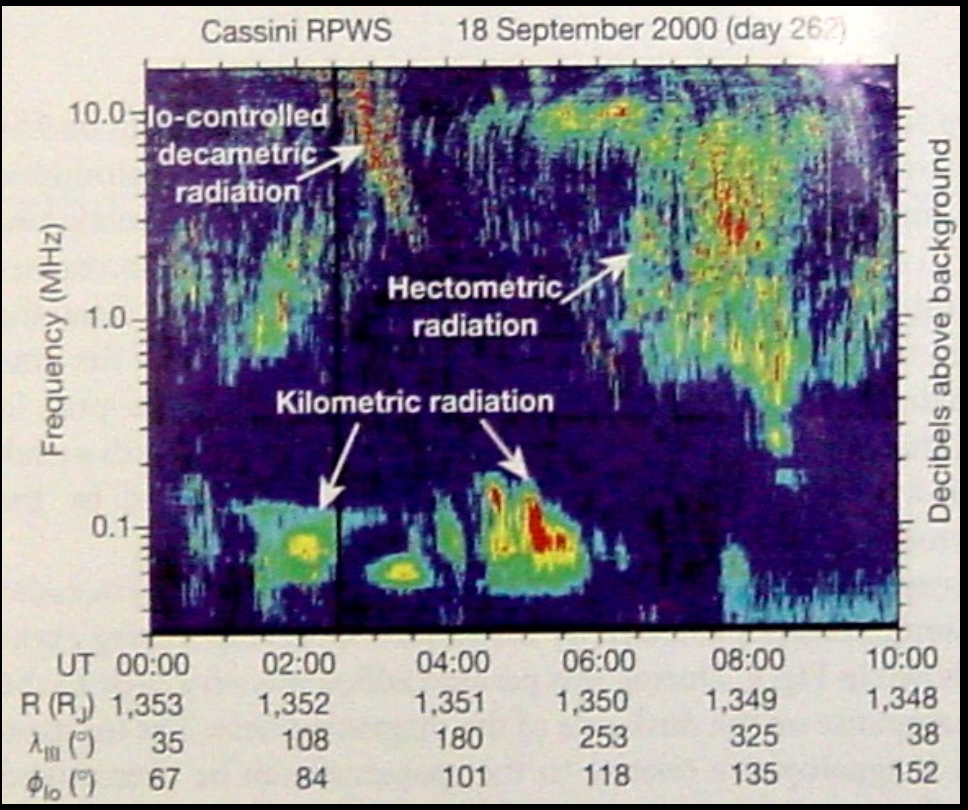
- What are mechanisms and sites of particle acceleration?
- How do CME interactions produce solar energetic particle (SEP) events?

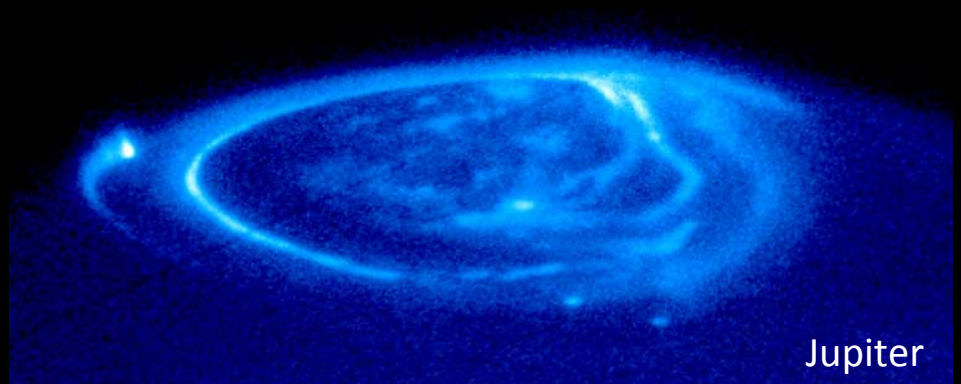
➢ Need imaging

… though considerable progress to date via dynamic spectra



Planetary Radio Emission





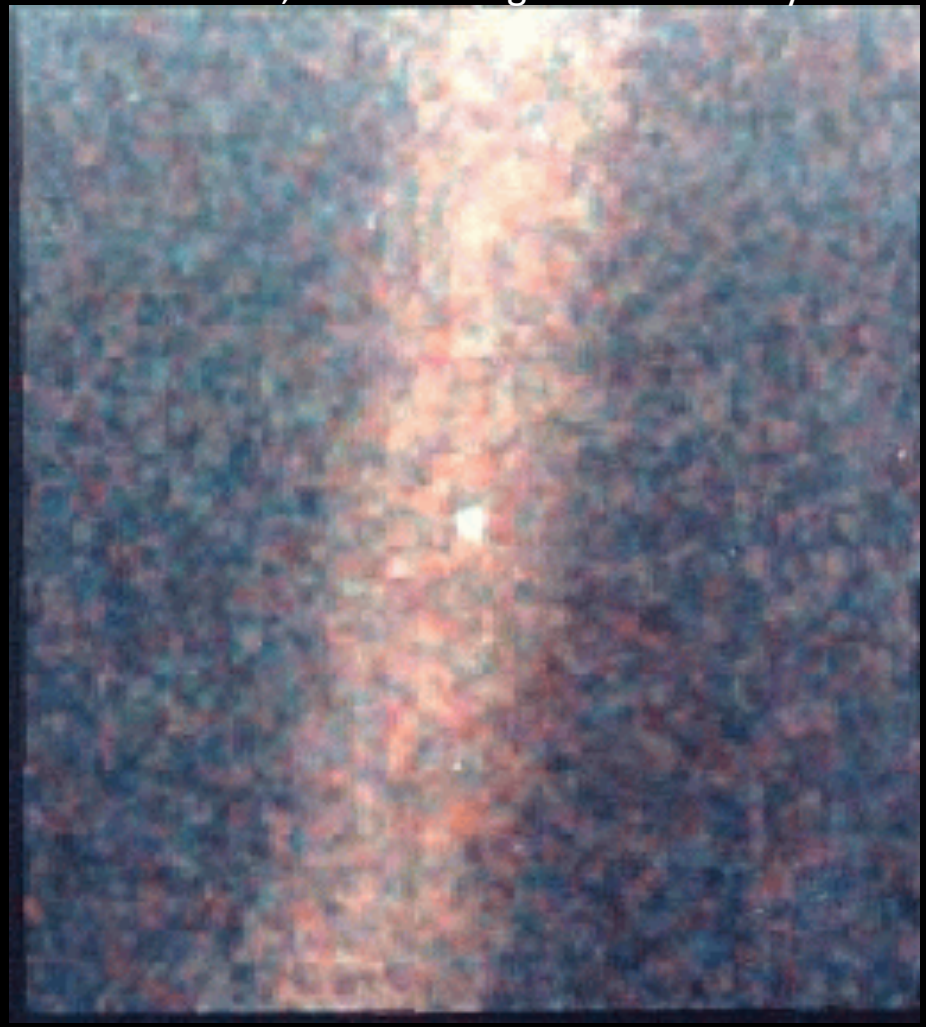
- Burke & Franklin (1955) discover radio emission from Jupiter
- Late 1960s/70s: Earth's polar region recognized as strong radio source (10^7 W)
- Voyager era: Opens field up
- ➢ All gas giants and Earth have planetary-scale magnetic fields.
- Gas giants have stong polar electron cyclotron radio emission.
  - Jupiter: Strongest at 10^{12} W, Io-driven *and* non-Io component
- Most components driven by solar wind-magnetosphere interaction.
- Provides shielding of Earth's atmosphere from solar wind
- Extrasolar planets … ?
  - First suggestions as early as 1977

Finding Earth

Can we find a nearby, *habitable* extrasolar planet?

- Lunar-based (or near lunar-based?) camera could be used to observe Earth as an extrasolar planet.
  - Camera for Lunar Observations of the Variable Earth (CLOVE, Sparks et al.)
  - Lunar Observatory for Unresolved Polarimetry of Earth (LOUPE)

Earth, from the edge of our solar system



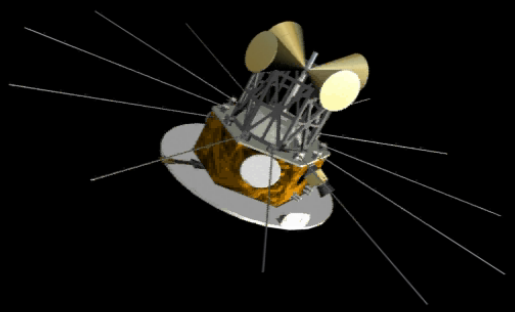
Lunar Radio Antennas and Telescopes

Science every step of the way
Gradually increasing capability and complexity

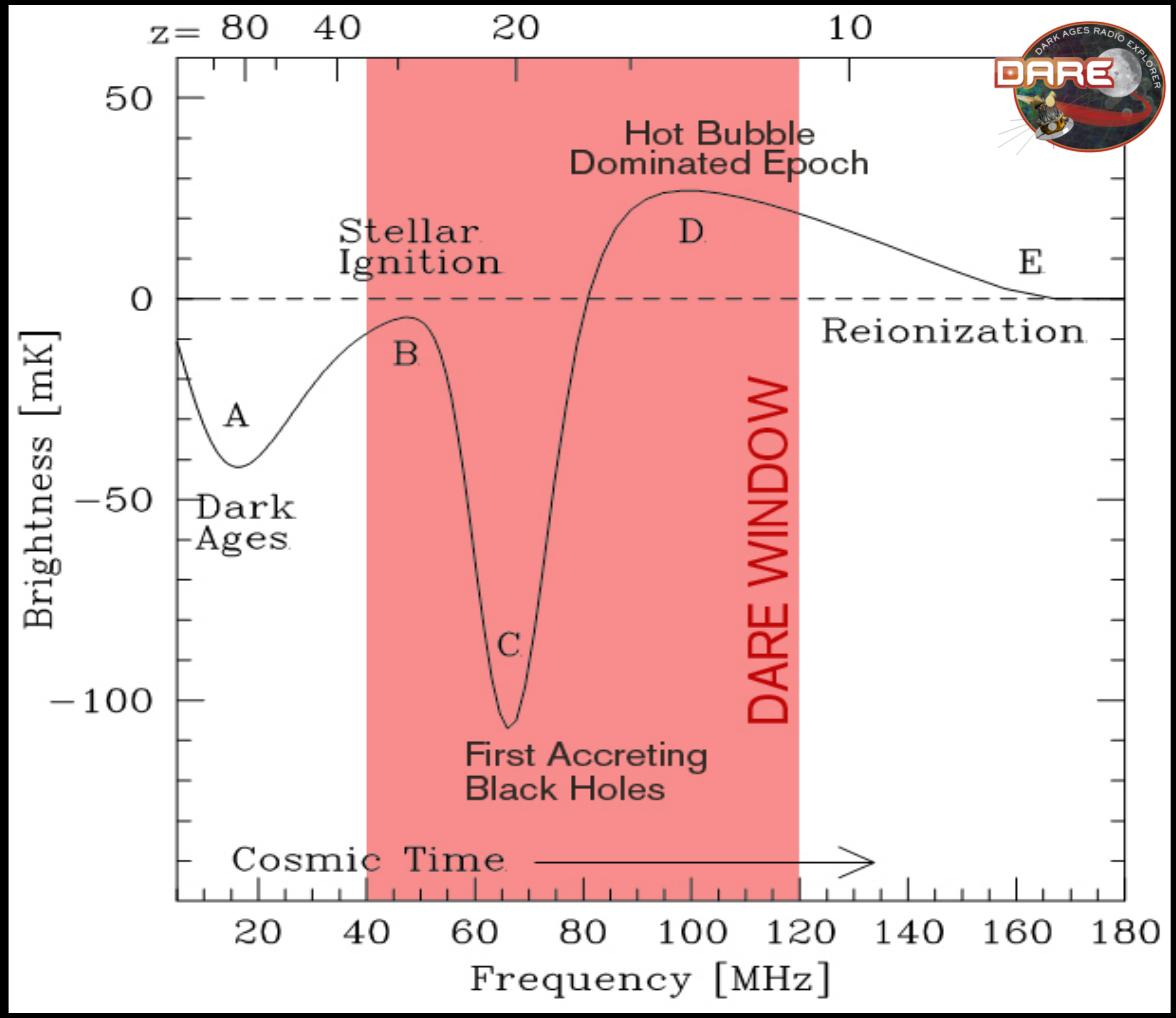
Key Science / *Concept*	Location	Frequency	Dimensions / Number of Antennas
Cosmic Dawn & Dark Ages *lunar orbiter - Dark Ages Radio Explorer*	Orbiting, over farside	40–120 MHz	2 m / 2 antennas
lunar ionosphere *Lunar Atmosphere Probe Station*	Near- or farside	0.1–3 MHz	< 50 m / 1+ antenna
Cosmic Dawn & Dark Ages *Cosmology Dipole*	Farside	40–120 MHz	< 10 m / 2 antennas
heliophysics and space weather *Radio Observatory on the Lunar Surface for Solar Studies (ROLSS)*	Near- or farside	1–10 MHz	~ 1 km / 100 antennas
Dark Ages and Cosmic Dawn *Lunar Radio Array*	Farside	10–100 MHz	~ 10 km / 10^4 antennas

Dark Ages Radio Explorer
Stage Ia: Lunar Orbiter

- DARE carries a single, high-heritage instrument operating at 40-120 MHz
- Components of all three subsystems (antenna, receiver and spectrometer) are at TRL ≥ 6
- Work underway to have the integrated instrument at TRL 6

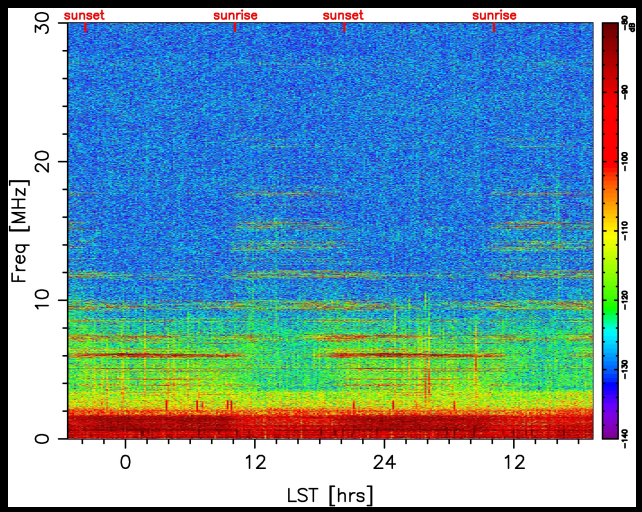


Burns et al. (2012, *Adv. Space Res.* **49**, 433)



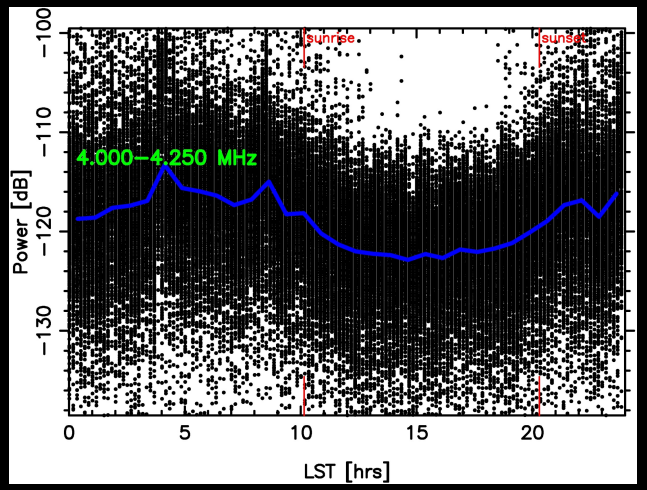
From Pritchard & Loeb (2010, *Phys. Rev. D*, **82**, 023006)

Surface Antenna Concept
Polyimide Film Antenna Field Tests



- 5 µm thick Cu layer deposited on 25 µm thick Kapton
- Dipole arm was 8 m long and 30.5 cm wide
- Inner 1 m of each arm tapered to a point at which a 1:1 wideband balun attached
- Good agreement with models (*not shown*)
- Spectrum recorded from 1–30 MHz every 10 min for just over 2 days
- Local noon occurred at LST ~ 15 hrs

➢ Decrease in power below 7 MHz is due to absorption by the D layer of the ionosphere



Lunar Atmosphere Probe Station

Stage Ib: Surface Antenna

"Planetary exospheres [on] the Moon, Mercury, asteroids, and some of the satellites of the giant planets, are poorly understood …."

Visions and Voyages for Planetary Science

"The lunar atmosphere … is the nearest example of a surface boundary exosphere, the most common type of satellite atmosphere in the solar system."

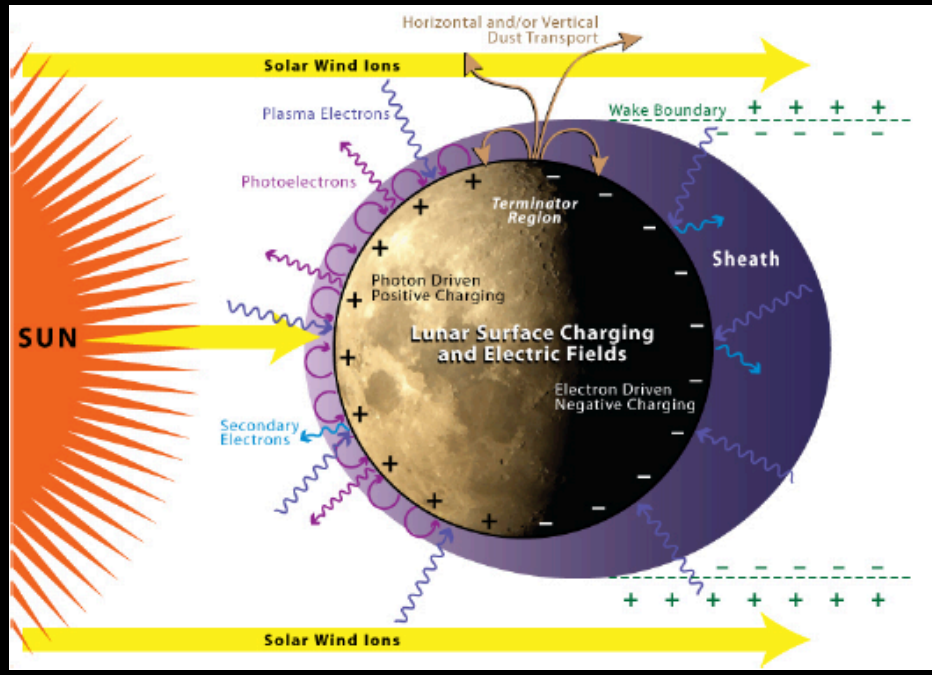
Scientific Context for the Exploration of the Moon

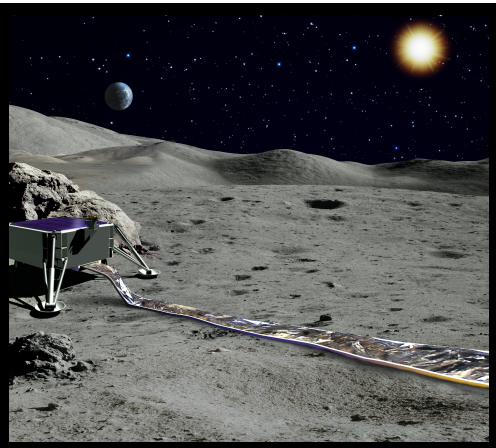
Provide lunar surface based method for tracking density of lunar exosphere.

- Electromagnetic waves below plasma frequency cannot propagate:

$$f_p = 9 \text{ kHz } \sqrt{n_e}$$

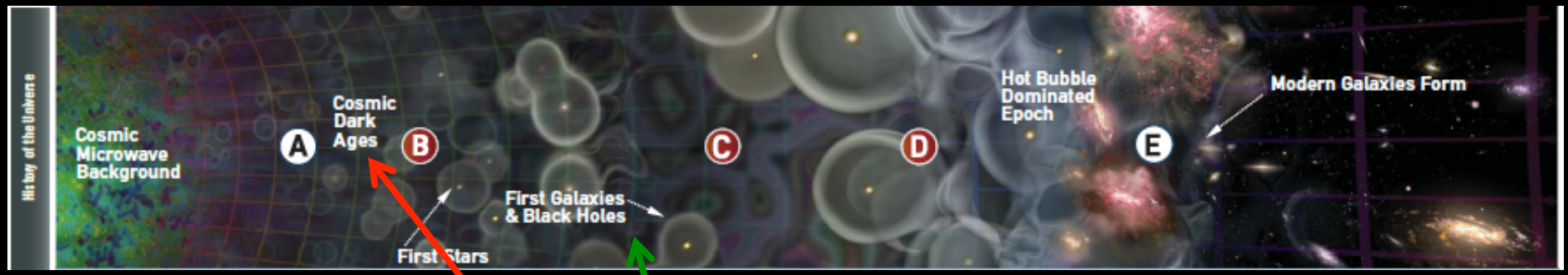
- Existing measurements suggest variable exosphere, both in density and altitude
  - 10^3 to 10^4 cm^{-3}
  - Up 10 km
- Spacecraft based measurements subject to (well-known) systematic errors





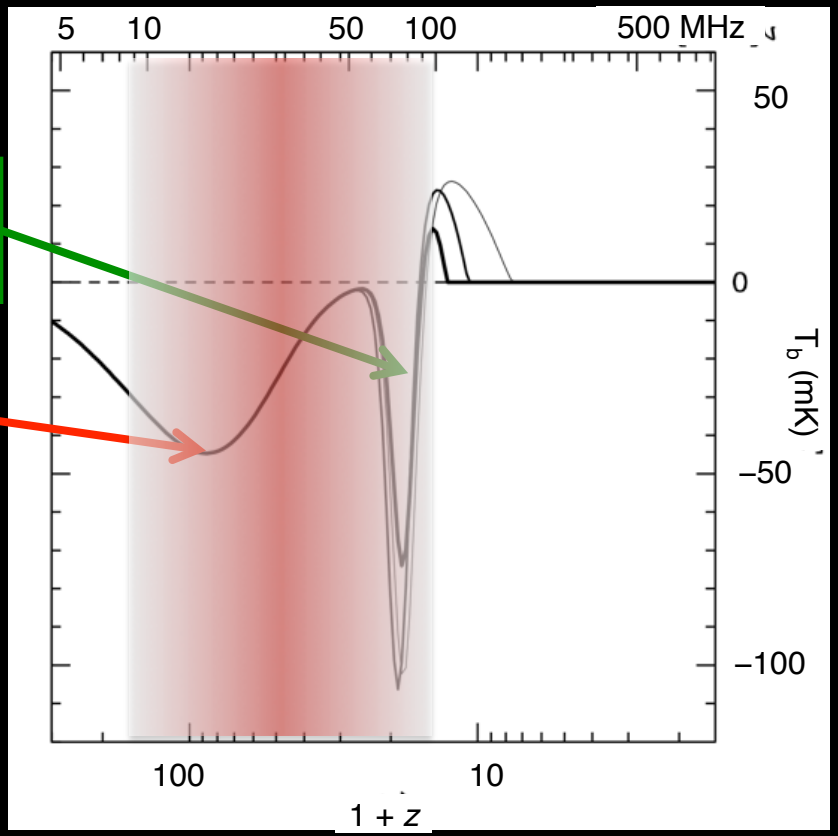
Cosmology Dipole

Stage Ib: Farside Surface Antenna



Cosmic Dawn

Dark Ages



Surface Antenna Concept
Deployment Mechanisms

- Approaches
  - Inflatable
  - Javelin
  - Rover
  - Mix-n-match
- Suitable for deployment of other science instruments or infrastructure …

➢ *Not* robotic vs. human …

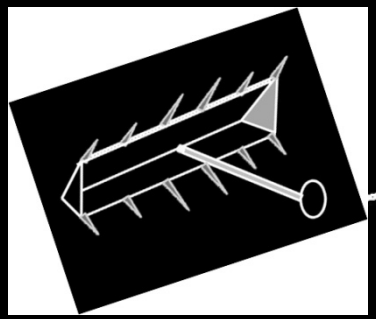
➢ Robotic ⇐⇒ Human

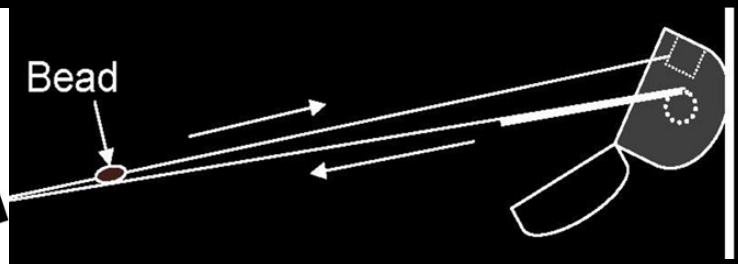
Inflatable (a.k.a. “party favor”) at JPL Mars Yard

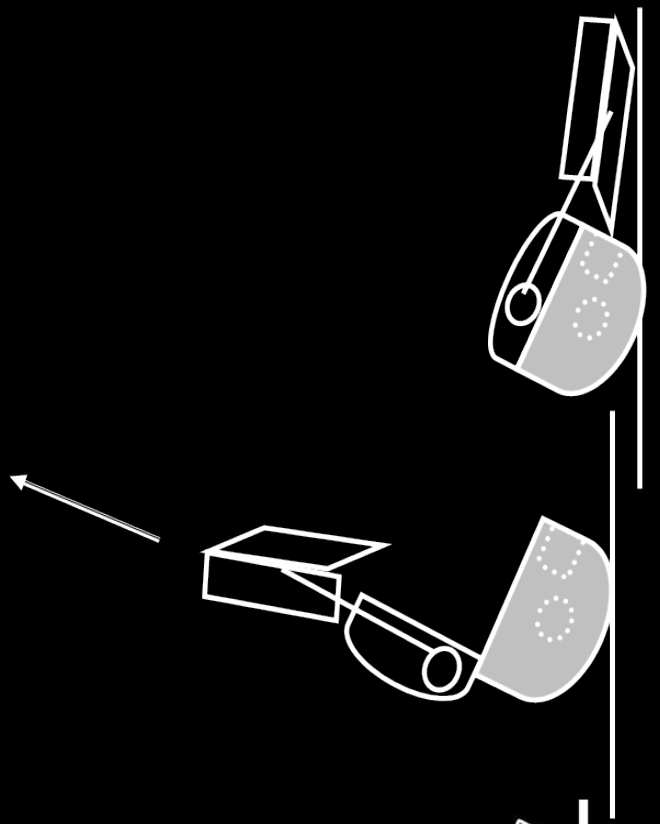
Anchor-Based Film Deployer

- Spring-launched anchor system concept to deploy polyimide film
  - … many possible designs
- Once anchor has deployed, motor pulls in line, pulling film & antennas off roll
- "Fractal" anchor reduces risk of anchor slipping

Anchor deployer at NASA/GSFC test site







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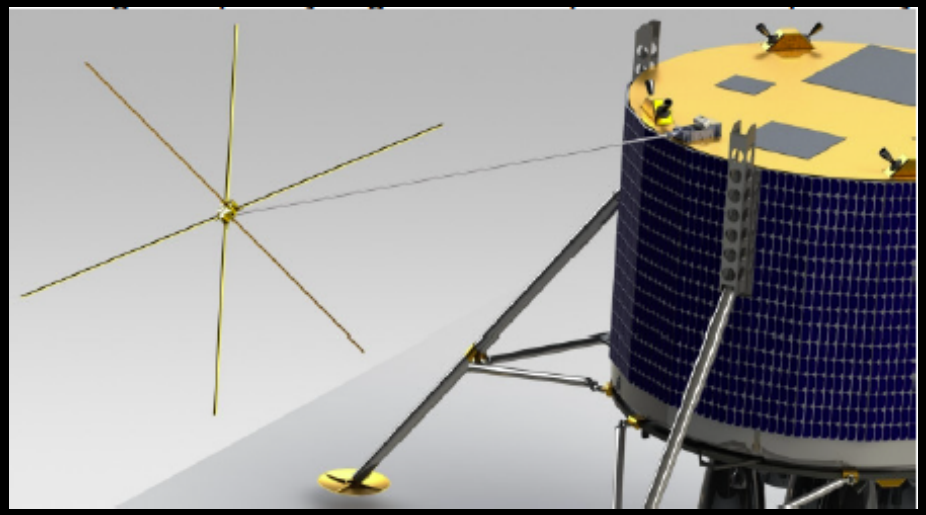
European Lunar Lander

- ELL targeted for South Pole
  - Prime mission is precision landing
- Lunar Radio Explorer (LRX) tripole antenna, deployed off side of ELL
  - Ionospheric measurements
    - Relative opacity measurements
  - Galactic radio spectrum
  - Planetary astronomy



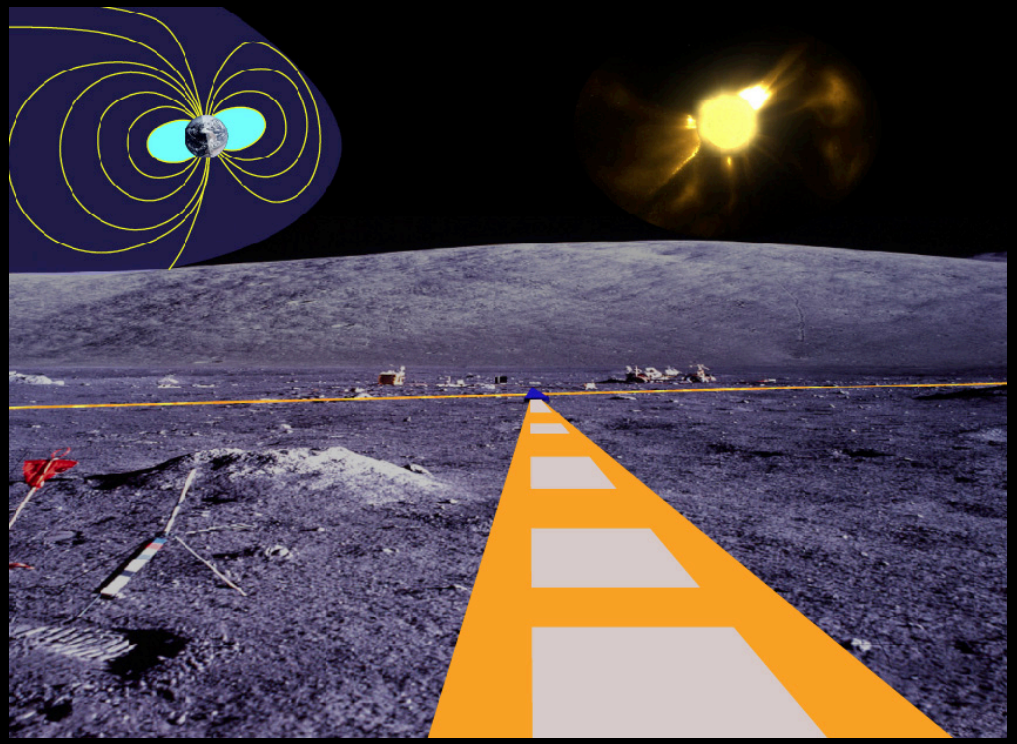
Lunar Radio Explorer (LRX), part of Lunar Dust Environment and Plasma Package (LDEPP), on ESA Lunar Lander

Radio Observatory on the Lunar Surface for Solar Studies

Stage II: Nearside Array

Imaging instrument capable of 2° resolution @ 30 m wavelength

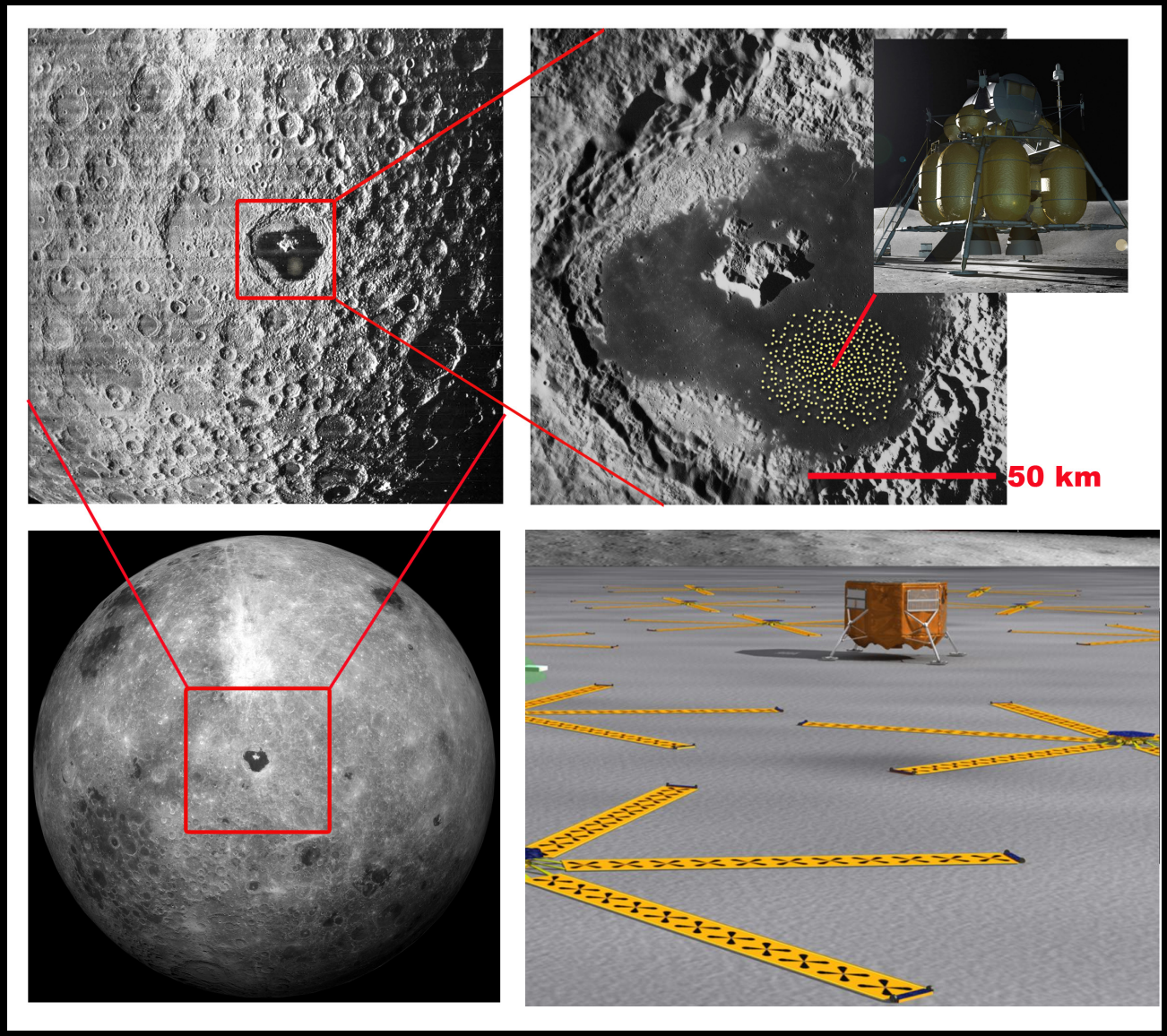
- 30–300 m wavelength (1–10 MHz frequency)
  - Relevant range for particle acceleration
  - Upper range for lunar ionosphere
  - Inaccessible from the ground
- 3-arm interferometer
  - 500 m long arms
    - First imaging instrument at these wavelengths
    - Order of magnitude improvement in resolution at these wavelengths



Lazio et al. (2011, *Adv. Space Res.*, **48**, 1942)

Lunar Radio Array

Stage III: Farside Array



Lunar Radio Antennas and Telescopes: Staged Approach

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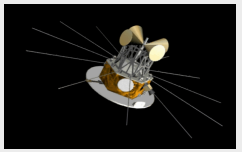
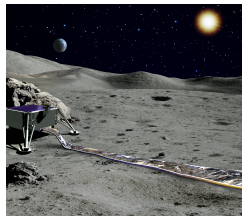
Cosmic Dawn & Dark Ages *lunar orbiter - Dark Ages Radio Explorer*	Orbiting, over farside	40–120 MHz	2 m / 2 antennas	
lunar ionosphere *Lunar Atmosphere Probe Station*	Near- or farside	0.1–3 MHz	< 50 m / 1+ antenna	
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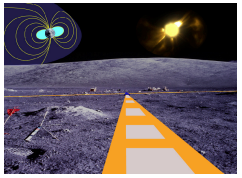
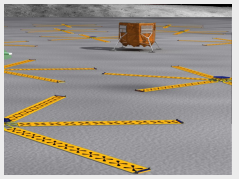
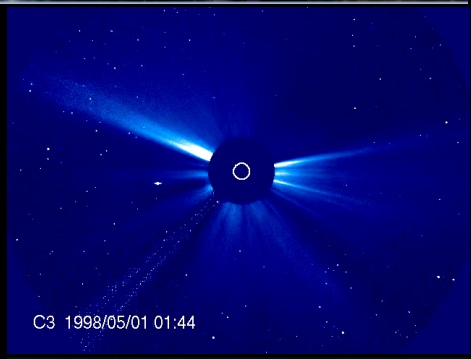
heliophysics and space weather *Radio Observatory on the Lunar Surface for Solar Studies (ROLSS)*	Near- or farside	1–10 MHz	~ 1 km / 100 antennas	
Dark Ages and Cosmic Dawn *Lunar Radio Array*	Farside	10–100 MHz	~ 10 km / 10^4 antennas	

From the Moon!

- Cosmology
- Heliophysics
- Astrobiology
- Lunar science
- Technology development
- Exploration



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